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# Is a high $P_T$ muon of the $e^+p \rightarrow \mu^+X$ event observed at HERA a signature of the stop?

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## Abstract

We investigate the  $e^+p \rightarrow \mu^+X$  event with high transverse momenta observed at HERA (H1) and show that this event could be interpreted as a signature of the single production of the scalar top quark in a supersymmetric model with  $R$ -parity breaking interactions. The event topology of the H1 event is rather characteristic and in fact it can be simulated by our specific scenario if we reasonably choose our model parameters to be (i)  $m_{\tilde{d},\tilde{b},\tilde{\nu}} \gtrsim 1\text{TeV}$  [0.8TeV] for  $\lambda'_{131} = 0.1$  [0.05] and (ii)  $m_{\tilde{W}_1} \lesssim 150\text{GeV}$ ,  $100\text{GeV} \lesssim m_{\tilde{t}_1} \lesssim 200\text{GeV}$  and  $\lambda'_{131} \gtrsim 0.05$ .

Recently the H1 group reported that an event with high transverse momenta had been observed [1] at HERA. The total data sample analyzed at the H1 group corresponds to an accumulated luminosity of  $3.2\text{pb}^{-1}$  in positron ( $27.5\text{GeV}$ ) – proton ( $820\text{GeV}$ ) collisions and of  $0.8\text{pb}^{-1}$  in electron – proton collisions. The event is characterized by (i) a large transverse momentum of the single muon  $\mu^+$ ,  $P_T(\mu) = 23.4 \pm 2.4_{-5}^{+7}\text{GeV}$ , (ii) a small  $\delta$  ( $\equiv \sum E(1 - \cos \theta)$ ),  $\delta = 19.2 \pm 1.6_{-2.1}^{+3.0}\text{GeV}$ , where  $E$  and  $\theta$  denote the energy and angle of any detected particle, (iii) a large transverse momentum of the total hadronic system,  $P_T(\text{hadron}) = 42.1 \pm 4.2\text{GeV}$  and (iv) a large missing transverse momentum  $P_T(\text{miss}) = 18.7 \pm 4.8_{-7}^{+5}\text{GeV}$ .

Some possible interpretations of the event have been given in ref.[1];

- (A) production of high  $P_T$  jets
- (B)  $W$  production and its leptonic decay
- (C) A flavour changing neutral currents (FCNC) or leptoquark production

However, it does not seem to give reasonable explanation of the event characterized by the topology mentioned above [1]. As for the scenario **A**, the probability for the event being due to the production of two high  $P_T$  jets, where one jet shows the signature of a muon, is smaller than  $10^{-3}$ . As for the scenario **B**, the  $W$  production and its leptonic decay would give a rather small transverse momentum of the total hadronic system. In fact, the Monte Carlo calculation shows that for  $P_T(\text{hadron}) > 40\text{GeV}$  the cross section is reduced to  $7\text{fb}$ . That is, with one event seen in  $4\text{pb}^{-1}$  we are left with a 3% probability for this interpretation of the event. As for the scenario **C**, expected events would have balanced  $P_T$  and a value of  $\delta = 2E_e$ . This is due to the fact that events originated from the FCNC or leptoquark production would show topologies like neutral current deep inelastic events, but with the final state positron replaced by a muon. The fact that less than 1% of neutral current events show a value of  $\delta < 20\text{GeV}$  disfavors this interpretation.

In this letter, we propose a possible explanation of the single muon event in the framework of the minimal supersymmetric (SUSY) standard model (MSSM). We will show that the high  $P_T$  muon could appear from the single scalar top quark (stop) production through an  $R$ -parity breaking coupling at HERA.

In the previous work [2], we have already shown that one of the signals of the single stop production to be detected at HERA is characterized by the high  $P_T$  spectrum of muons. First, for the sake of convenience we will briefly summarize the basic idea by referring to our previous work [2]. The discussion is based on the MSSM with an  $R$ -parity breaking (RB) interaction

$$L = \lambda'_{131} \cos \theta_t (\tilde{t}_1 \bar{d} P_L e + \tilde{t}_1^* \bar{e} P_R d), \quad (1)$$

where  $\lambda'_{131}$  and  $\theta_t$ , respectively, denote the coupling strength and the mixing angle of the stops [3, 4]. Here  $P_{L,R}$  read left and right handed chiral projection operators. The interaction Lagrangian (1) has been originated from the general RB superpotential [5];

$$W_R = \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^c + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k^c + \lambda''_{ijk} \hat{U}_i^c \hat{D}_j^c \hat{D}_k^c, \quad (2)$$

where  $i, j, k$  are generation indices. The first two terms violate the lepton number  $L$  and the last term violates the baryon number  $B$ . If we want to explain such unresolved problems as (i) the cosmic baryon number violation, (ii) the origin of the masses and the magnetic moments of neutrinos and (iii) some interesting rare processes in terms of the  $L$  and/or  $B$  violation, the  $R$ -parity breaking terms must be incorporated in the MSSM.

The coupling Eq. (1) will be most suitable for the  $ep$  collider experiments at HERA because the stop will be produced in the  $s$ -channel in  $e$ - $q$  sub-processes [2, 6]

$$ep \rightarrow \tilde{t}_1 X. \quad (3)$$

Note that the stop cannot couple to any neutrinos via  $R$ -breaking interactions. This is a unique property of the stop which could be useful for us to distinguish the stop from some leptoquarks. Production processes of the first and second generation squarks have been discussed in ref.[7].

Babu and Mohapatra [8] have recently shown that the severe constraint on a product  $\lambda'_{113}\lambda'_{131} \lesssim 3 \times 10^{-8}$  comes from experimental data of the neutrinoless double  $\beta$  decays. Here, we will assume  $\lambda'_{131}$  to be only non-zero coupling parameter in what follows. The upper bound on the strength of the coupling has been investigated through the low-energy experiments [5] and the neutrino physics [9]. The most stringent bound  $\lambda'_{131} \lesssim 0.25$  comes from the atomic parity violation experiment [5].

Next we examine the decay modes of the stop. In the MSSM, the stop lighter than the other squarks and gluino can decay into the various final states :

$$\begin{aligned} \tilde{t}_1 &\rightarrow t \tilde{Z}_k & (a) \\ &\rightarrow b \tilde{W}_i & (b) \\ &\rightarrow b \ell \tilde{\nu} & (c) \\ &\rightarrow b \nu \tilde{\ell} & (d) \\ &\rightarrow b W \tilde{Z}_k & (e) \\ &\rightarrow b f \bar{f}' \tilde{Z}_k & (f) \\ &\rightarrow c \tilde{Z}_1 & (g) \\ &\rightarrow e d, & (h) \end{aligned}$$

where  $\tilde{Z}_k$  ( $k = 1 \sim 4$ ),  $\tilde{W}_i$  ( $i = 1, 2$ ),  $\tilde{\nu}$  and  $\tilde{\ell}$ , respectively, denote the neutralino, the chargino, the sneutrino and the charged slepton. (a)  $\sim$  (g) are the  $R$ -parity conserving decay modes, while (h) is only realized through the RB couplings (1).

If we consider the stop with mass small enough in the case of the  $R$  conserving coupling, the first five decay modes (a) to (e) are kinematically forbidden due to the observed top mass  $m_t \simeq 175$  GeV [10] as well as the model independent lower mass bounds for sparticles ;  $m_{\tilde{W}_1} \gtrsim 45$  GeV,  $m_{\tilde{\ell}} \gtrsim 45$  GeV and  $m_{\tilde{\nu}} \gtrsim 40$  GeV. So (f) and (g) survive. Hikasa and Kobayashi [4] have shown that the one-loop mode (g)  $\tilde{t}_1 \rightarrow c \tilde{Z}_1$  dominates over the four-body mode (f)  $\tilde{t}_1 \rightarrow b f f' \tilde{Z}_1$ . So we can safely conclude that such a light stop will decay into the charm quark jet plus the missing momentum taken away by the neutralino with almost 100% branching ratio. On the other hand, if we consider the RB coupling  $\lambda'_{131} > 0.01$ , which roughly corresponds to the coupling strength to be detectable at HERA, the decay modes (c) to (g) are negligible due to their large power of  $\alpha$  arising from multiparticle

final state or one loop contribution. Then only two body decay modes (a), (b) and (h) are left for our purpose.

We have found [2] that if the stop is heavy enough, i.e.,  $m_{\tilde{t}_1} > m_b + m_{\tilde{W}_k}$  and the RB coupling is comparable with the gauge or Yukawa coupling  $\lambda'_{131}/4\pi \lesssim \alpha, \alpha_t$  there is a wide range of parameters where  $BR(\tilde{t}_1 \rightarrow b\tilde{W}_k)$  dominance over  $BR(\tilde{t}_1 \rightarrow ed)$  is assumed.

In this case, we should take into account of the process

$$ep \rightarrow b\tilde{W}_k X, \quad (4)$$

where the virtual contributions of the sneutrino with the same RB coupling constants  $\lambda'_{131}$  have, of course, been considered. The differential cross section is given by

$$\begin{aligned} \frac{d\sigma}{dx dQ^2}(ep \rightarrow b\tilde{W}_k X) &= \frac{\alpha \lambda_{131}^2}{16\hat{s}^2 \sin^2 \theta_W} \left[ |V_{11}|^2 \frac{(\hat{u} - m_b^2)(\hat{u} - m_{\tilde{W}_k}^2)}{(\hat{u} - m_\nu^2)^2} \right. \\ &+ \frac{\cos^2 \theta_t \hat{s}}{(\hat{s} - m_{\tilde{t}_1}^2)^2 - m_{\tilde{t}_1}^2 \Gamma_{\tilde{t}_1}^2} \left( (|G_L|^2 + |G_R|^2)(\hat{s} - m_b^2 - m_{\tilde{W}_k}^2) - 4m_b m_{\tilde{W}_k} \text{Re}(G_R G_L^*) \right) \\ &\left. - \frac{2 \cos^2 \theta_t \hat{s}(\hat{s} - m_{\tilde{t}_1}^2)}{((\hat{s} - m_{\tilde{t}_1}^2)^2 + m_{\tilde{t}_1}^2 \Gamma_{\tilde{t}_1}^2)} \text{Re} \left( V_{11}^* (G_R \hat{u} + G_L m_b m_{\tilde{W}_k}) \right) \right], \end{aligned} \quad (5)$$

with  $\hat{s} = xs, \hat{t} = -Q^2$  and

$$G_L \equiv -\frac{m_b U_{k2}^* \cos \theta_t}{\sqrt{2} m_W \cos \beta}, \quad (6)$$

$$G_R \equiv V_{k1} \cos \theta_t + \frac{m_t V_{k2} \sin \theta_t}{\sqrt{2} m_W \sin \beta}. \quad (7)$$

Here  $V_{kl}$  and  $U_{kl}$  stand for the chargino mixing angles [11]. The mixing angles as well as masses of the neutralinos  $m_{\tilde{Z}_i}$  and the charginos  $m_{\tilde{W}_k}$  are determined from the basic parameters in the MSSM ( $\mu, \tan \beta, M_2$ ). We can see that the  $e^+$  beam is more efficient than the  $e^-$  one to distinguish the stop signal from the SM background. This can be understood from the fact that the  $e^+$  collides with valence  $d$ -quark in the proton, while the  $e^-$  does only with sea  $\bar{d}$ -quarks. It is expected that the detectable cross sections  $\sigma \gtrsim 0.1$  pb for heavy stop with mass  $m_{\tilde{t}_1} \lesssim 250$  GeV for  $e^+$  beams. As far as  $e^-$  beams are concerned  $e^- p \rightarrow b\tilde{W}_k X$  would be detectable for  $m_{\tilde{t}_1} \lesssim 170$  GeV. In our model the LSP, the lightest neutralino  $\tilde{Z}_1$  possibly decays into  $R$ -even particles via only non-zero RB coupling  $\lambda'_{131}$ . A typical decay chain will be

$$ep \rightarrow b\tilde{W}_1 X \rightarrow (b\ell\nu\tilde{Z}_1)X \rightarrow b(\ell\nu(bd\nu))X. \quad (8)$$

Thus, a possible typical signature of the stop production  $ep \rightarrow b\tilde{W}_1 X$  would be  $b$ -jet+lepton+ $\cancel{P}_T$  in the case of no LSP decay or  $2b$ -jets+jet+lepton+ $\cancel{P}_T$  in the case of the LSP decay via RB coupling. One of the signals to be detected at HERA is characterized by the high  $P_T$  spectrum of muons. The lower  $P_T$  cut certainly makes the event distinctive from its background. The cross section  $\sigma(e^+ p \rightarrow \tilde{t}_1 X \rightarrow b\tilde{W}_1 X)$  varies from 1 to 10pb depending on mass of the stop in the range of  $100 \sim 150$  GeV.

Now it is the position to present our calculation for some kinematical distributions in the process (8), which will also be compared to the experimental distributions of the H1 event [1].

First, the  $P_T(\mu)$  distribution of the expected number of events is shown in Fig.1. In the calculation, we take a typical set of model parameters,  $(\mu, M_2, \tan\beta, m_t, \theta_t, \lambda'_{131}) = (-300\text{GeV}, 50\text{GeV}, 2, 175\text{GeV}, 1.0\text{rad}, 0.1)$  and the integrated luminosity  $3.2\text{pb}^{-1}$ . In this case we get the lighter chargino mass  $m_{\tilde{W}_1} = 63\text{GeV}$  and the lightest neutralino mass  $m_{\tilde{Z}_1} = 28\text{GeV}$ . For simplicity, the branching ratio  $BR(\tilde{W}_1 \rightarrow \nu\mu\tilde{Z}_1)$  is assumed to be  $\frac{1}{9}$ [12]. The dependence on the branching ratio of the chargino will be discussed later. We find in Fig.1 that rather heavy stop,  $m_{\tilde{t}_1} = 100 \sim 120$ , could give a high  $P_T(\mu)$  event at the present integrated luminosity.

We show the  $\delta$  distribution together with the experimental data in Fig.2. The observed value of  $\delta$  is significantly smaller than the allowed maximum value  $2E_e$ . Such  $\delta$  could be obtained only when the LSP does not decay via the RB couplings in the detector. This constraint leads to following important consequences. We can quantitatively present the requirement as  $c\gamma\tau_{\tilde{Z}_1} \gtrsim 1\text{m}$ , which corresponds to  $\Gamma_{\tilde{Z}_1} \lesssim 10^{-7}\text{eV}$ . By calculating the 3-body LSP decay width, we get severe constraints,  $m_{\tilde{d},b,\tilde{\nu}} \gtrsim 1\text{TeV}$  [0.8TeV] for  $\lambda'_{131} = 0.1$  [0.05]. Another one is that the total transverse hadronic momentum should be supplied by a  $b$  quark at the first vertex in the process (8). In other words, we can take  $P_T(b) \simeq P_T(\text{hadron})$  in our model calculation. Note, moreover, that large masses of sfermions justify our assumption on the chargino decay,  $BR(\tilde{W}_1 \rightarrow \nu\mu\tilde{Z}_1) \simeq \frac{1}{9}$ . When sfermions are sufficiently heavy the dominant contribution to the decay matrix elements comes from the  $W$ -boson exchange diagram, which has apparently universal fermion couplings.

Shown in Fig.3 is the  $P_T(b)$  ( $\simeq P_T(\text{hadron})$ ) distribution. From the figure, we find that heavier stop is favourable to simulate the large transverse hadronic momentum  $\sim 40\text{GeV}$ . Note that the maximum value of  $P_T(b)$  is determined from the simple kinematics of the two-body decay,

$$E_b^{max} = \frac{1}{2m_{\tilde{t}_1}}(m_{\tilde{t}_1}^2 + m_b^2 - m_{\tilde{W}_1}^2). \quad (9)$$

Consequently, we can restrict possible regions in  $(m_{\tilde{W}_1}, m_{\tilde{t}_1})$  parameter space in terms of the experimental constraint,  $P_T(b) \gtrsim P_T^{exp}(\text{hadron}) \simeq 40\text{GeV}$ .

We present such a experimentally favourable region (shaded area) in Fig.4. Horizontal (dotted) lines correspond to one event with  $P_T(\mu) > 20\text{GeV}$  to be expected. It is seen from the figure that constraints have been set on the masses  $m_{\tilde{W}_1}$  and  $m_{\tilde{t}_1}$ , if we seriously take into account the present data. For example, the chargino mass is smaller than about  $100\text{GeV}$  for  $\lambda'_{131} \lesssim 0.1$  under the condition of  $P_T(b) \gtrsim 40\text{GeV}$ . Moreover,  $\lambda'_{131}$  should be larger than about 0.05 and the stop mass should be larger than about  $100\text{GeV}$  because of the LEP bound on  $m_{\tilde{W}_1} > 45\text{GeV}$ . As has already been mentioned, low energy experiments set the constraint  $\lambda'_{131} \lesssim 0.25$ .

We have investigated a possible scenario to explain the H1 single muon event by the single production of the stop with an  $R$ -parity breaking interaction in the framework of the MSSM. The event topology of the H1 event is rather characteristic and in fact they can be simulated by our specific scenario if we restrict arbitrary model parameters to some

reasonable ranges. In order to work our scenario, we must have (i)  $m_{\widetilde{d,b},\widetilde{\nu}} \gtrsim 1\text{TeV}$  [0.8TeV] for  $\lambda'_{131} = 0.1$  [0.05], (ii)  $m_{\widetilde{W}_1} \lesssim 150\text{GeV}$ ,  $100\text{GeV} \lesssim m_{\widetilde{t}_1} \lesssim 200\text{GeV}$  and  $\lambda'_{131} \gtrsim 0.05$ .

Our scenario would be confirmed or rejected at LEP2 or next linear colliders through the search for  $e^+e^- \rightarrow \widetilde{W}_1^+\widetilde{W}_1^-$ . Certainly, the discovery of the chargino could reveal us that the nature is supersymmetric but could give no information as to whether or not the nature does not respect the  $R$ -parity. To confirm it, we should seek for the stop with the  $R$ -parity breaking interaction, e.g., through a search for  $e^+e^- \rightarrow e d \widetilde{t}_1$ . Needless to say, for our purpose it would be highly desirable to carry out the high luminosity run at HERA.

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## Figure Captions

**Figure 1:**  $P_T(\mu)$  distribution of the expected number of events together with the experimental data. We take  $(\mu, M_2, \tan\beta, m_t, \theta_t, \lambda'_{131}) = (-300\text{GeV}, 50\text{GeV}, 2, 175\text{GeV}, 1.0\text{rad}, 0.1)$  and the integrated luminosity as  $3.2\text{pb}^{-1}$ . Solid line and dotted line respectively correspond to  $m_{\tilde{t}_1} = 120\text{ GeV}$  and  $m_{\tilde{t}_1} = 100\text{ GeV}$ .

**Figure 2:**  $\delta$  distribution of the expected number of events together with the experimental data. We take  $m_{\tilde{t}_1} = 100\text{ GeV}$  and the same parameters in Fig.1. Solid line and dotted line respectively correspond to no LSP decay and the LSP decay within the detector.

**Figure 3:**  $P_T(b)$  ( $\simeq P_T(\text{hadron})$ ) distribution of the expected number of events together with the experimental data. Parameters are the same in Fig.1.

**Figure 4:** Favourable region (shaded area) in  $(m_{\tilde{W}_1}, m_{\tilde{t}_1})$  parameter space by the experimental constraint,  $P_T(b) \simeq P_T^{exp}(\text{hadron}) = 42.1 \pm 4.2\text{GeV}$ . Horizontal (dotted) lines correspond to one event with  $P_T(\mu) > 20\text{GeV}$  to be expected.



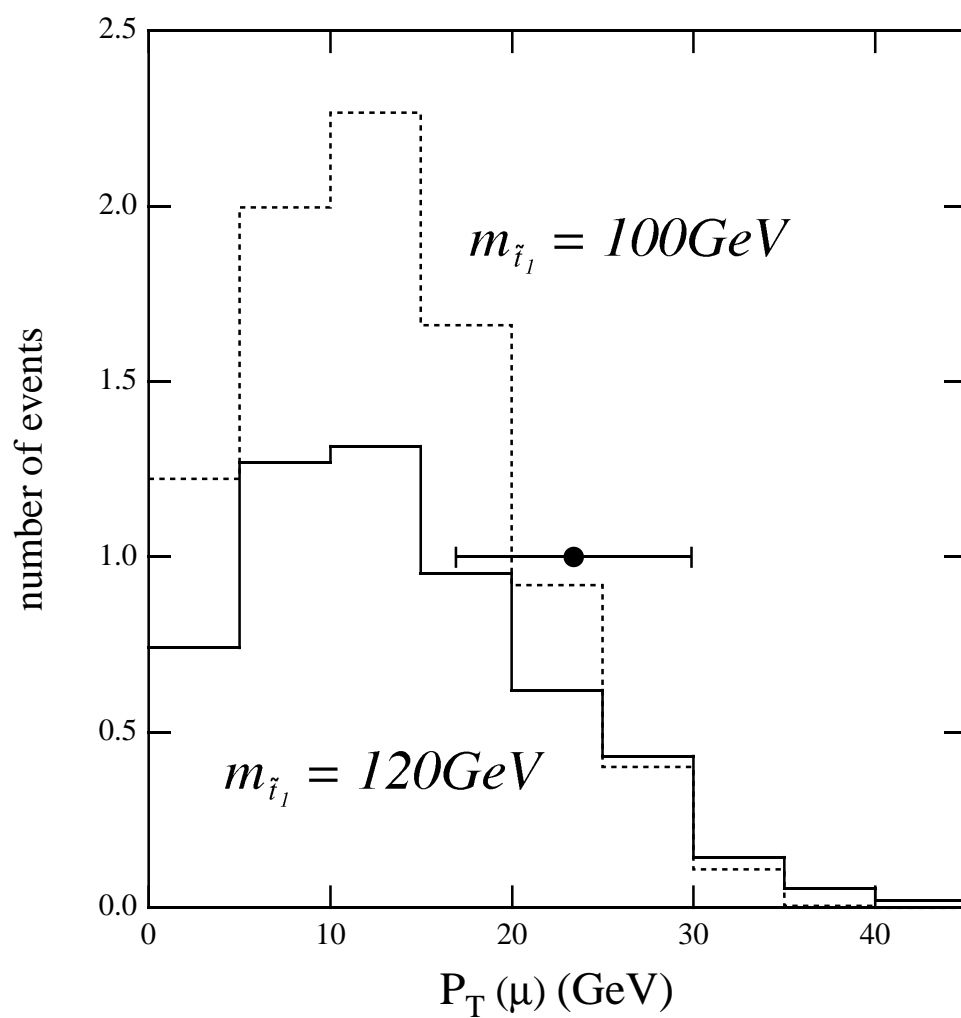


Fig.1

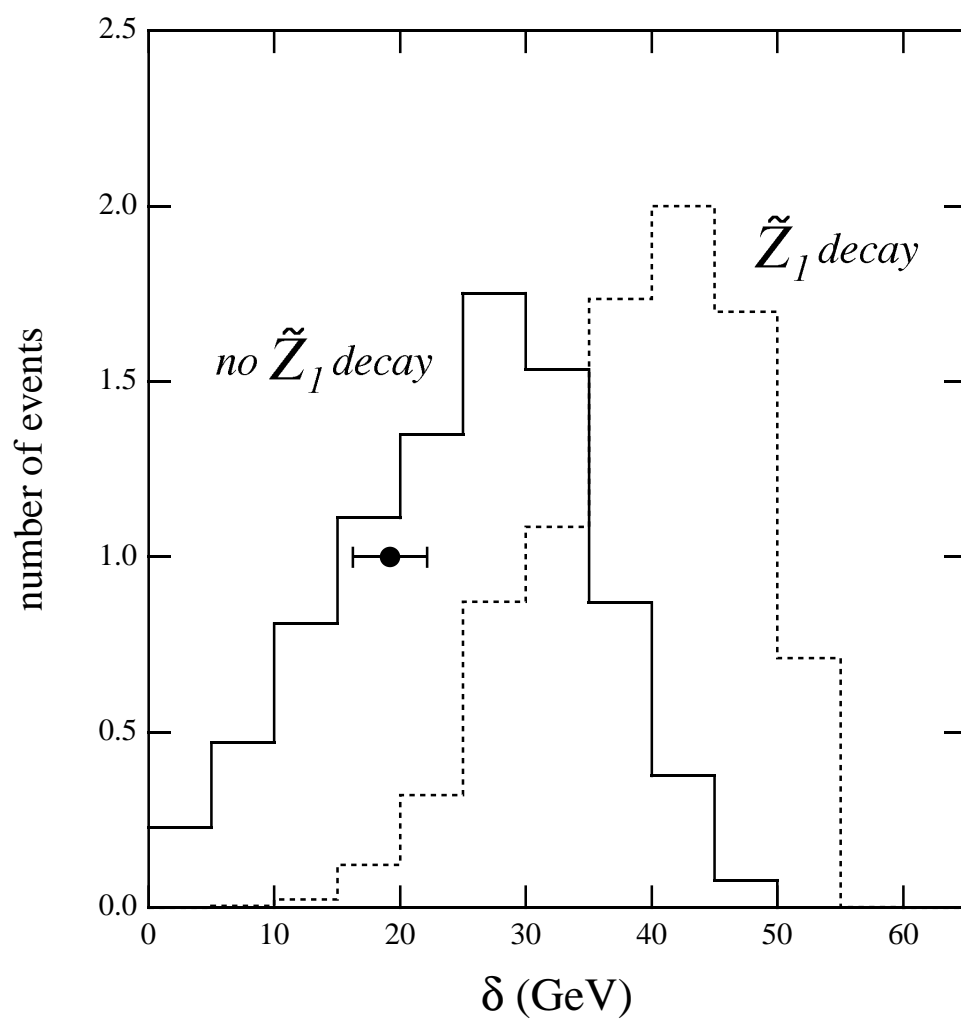


Fig.2

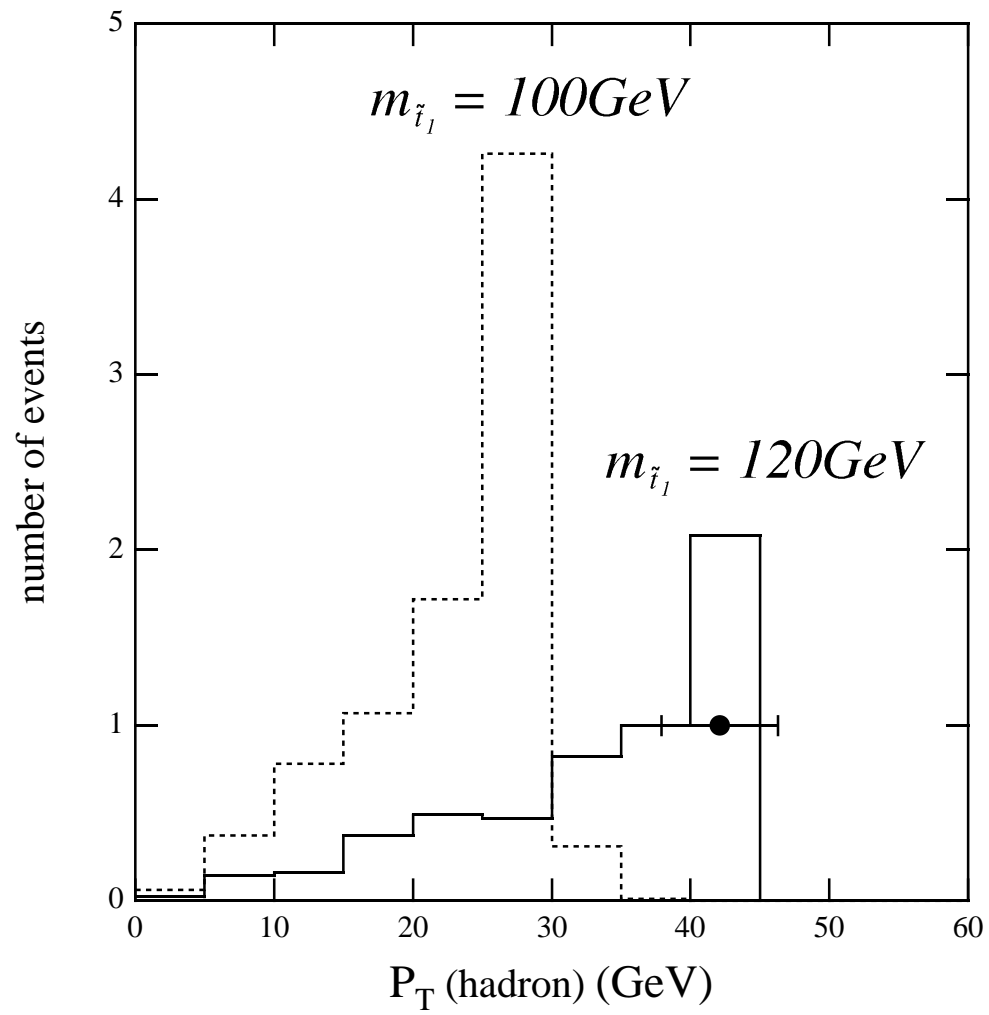


Fig.3

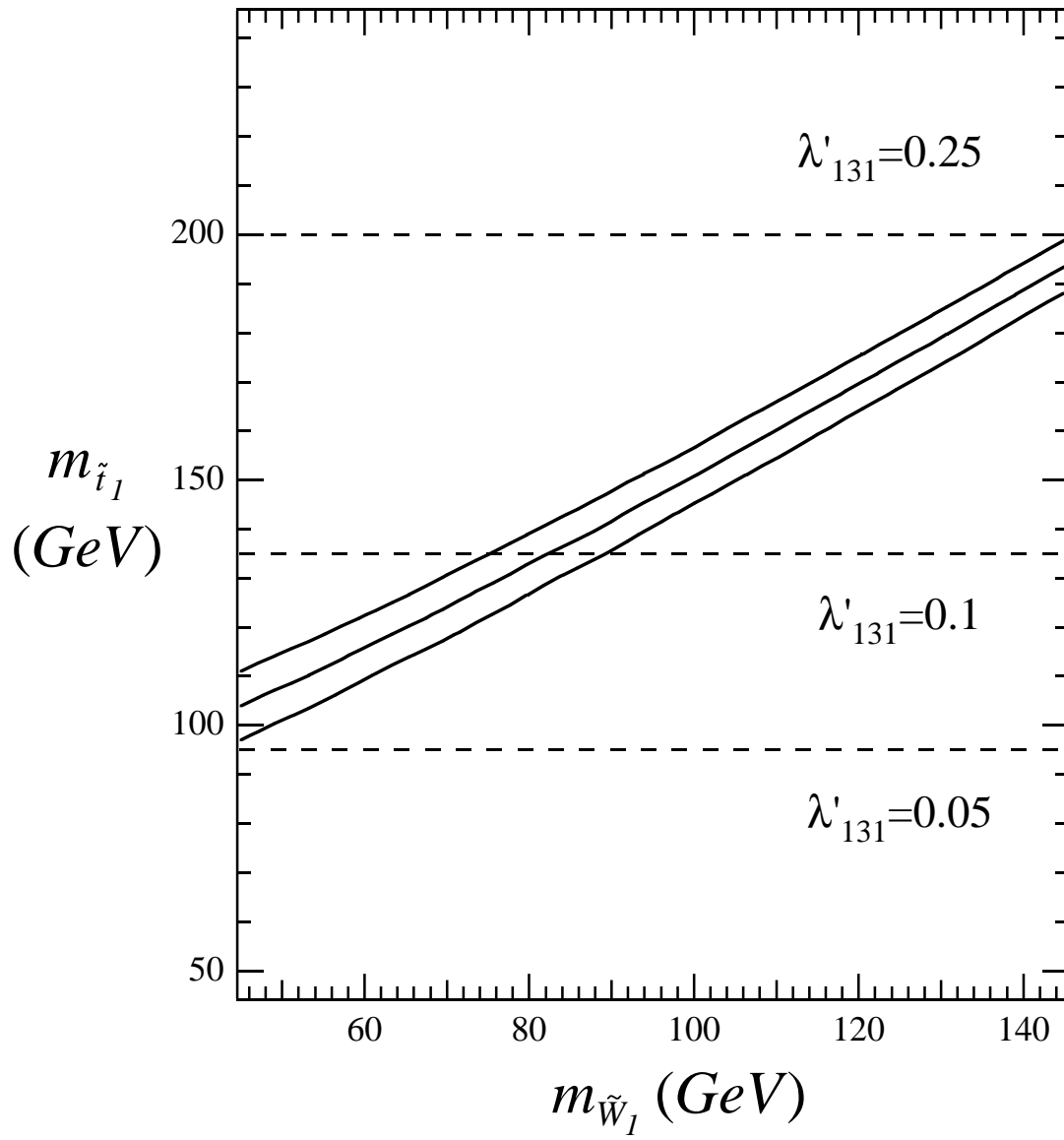


Fig.4